Comparing environmental and personal health impacts of individual food choices

Christie Walker[a,*], Eileen R. Gibney[b], John C Mathers[c], Stefanie Hellweg[a]

[a] Institute of Environmental Engineering, ETH Zurich, HPZ E33, John-von-Neumann-Weg 9, 8093 Zürich, Switzerland
[b] Institute of Food and Health, University College Dublin, Dublin 4, Ireland
[c] Human Nutrition Research Centre, Institute of Cellular Medicine, Newcastle University, Newcastle NE2 4HH, UK
[*] Corresponding author: Email: walker@ifu.baug.ethz.ch Phone: +41 44 633 7145

Abstract: Dietary choices affect personal health and environmental impacts, but little is known about the relation between these outcomes. Here we examine the intake-related health impacts and the food-production related impacts to ecosystems and human health by applying life cycle impact assessment methods to habitual diet data of 1457 European adults. We measured food production impacts for each individual in terms of Disability Adjusted Life Years (DALYs) as calculated by the Recipe 2016 life cycle impact assessment method using secondary production data, which were then compared with their personal health DALYs predicted from the known relationships between dietary choices and disease risk. Across this population cohort, each individual was estimated to lose on average 2.5±0.9 DALYs per lifetime due to sub-optimal dietary intake (with seed and vegetable under-consumption the greatest contributors) and their food choices caused environmental human health impacts of 2.4±1.3 DALYs (particularly due to the damage associated with production of meats, milk, and vegetables). Overall, there was no relationship between a healthier dietary pattern and the environmental human health impacts associated with production of its constituent foods (i.e. healthier diets did not have lower or higher production impacts). This was due to a combination of decreased meat consumption correlating with increased consumption of other foods, as well as the fact that under-consumption of some low impact foods yielded high personal health consequences. However, for specific food items synergies and tradeoffs could be identified. For example, reduced processed meat consumption benefits both personal and environmental health. Every DALY caused by higher whole grain and vegetable production and consumption would be offset by reduced disease risk that equated to an average of 7.7 (5.7 to 10.4) and 1.4 (0.9 to 2.5) lower personal health DALYs, respectively.

Keywords: disability adjusted life years; environmental impact; disease risk; healthful diets

1. Introduction

Most individuals make multiple eating decisions daily[1], with quality, price, taste, and health being the top factors influencing food choice[2,3], whereas the environmental consequences of such choices have been less important for most people[4,5,6]. However, food choices can have a significant environmental impact[7,8,9] as well as effects on long-term health[10,11,12,13].

Food production has a host of environmental impacts[14] and several life cycle impact assessment methods (LCIA) have been developed to quantify and characterize these environmental consequences[15,16]. While many LCIA methods quantify single environmental consequences (e.g. IPCC Global Warming Potentials (GWP) only quantifies the production of greenhouse gasses in units of kg CO_2 equivalents), other LCIA methods, such as Recipe[15], Ecological Scarcity[17], TRACI[18], or LC-Impact[19], aggregate many environmental consequences into one or more endpoint value(s). In some LCIA methods, one of these endpoint values is measured as Disability Adjusted Life Years (DALYs), which quantifies the damage to human health as a consequence of aggregated environmental impacts. Damage to human health can result from cardiovascular and respiratory diseases caused by particulate matter emissions (e.g. in both primary food production and in food transport)[20], diseases due to toxicity (e.g. from pesticide use and subsequent contamination of foods and the environment)[21], diseases such as malaria and diarrhea due to climate change[22], or malnutrition as a result of water shortages for irrigation and reduced food production[23]. In addition to human health damage, food production also damages ecosystems through, for example, adverse effects on climate change, water use, eco-toxicity, land use, eutrophication, and biodiversity loss.

While the processes involved in primary production, processing, transporting, and consuming food can cause environmental impacts and also damage human health, over or under-consumption of certain foods can also affect health adversely[24]. The Global Burden of Disease (GBD) consortium has quantified the worldwide and regional disease burdens (measured as disability adjusted life years [DALYs]) due to over or under consumption of certain foods and nutrients[24].

Recent studies discussing the joint environmental and health (dys)benefits of dietary patterns have been summarized in Aleksandrowicz et al.[25] and Perignon et al.[26]. In many of these studies, hypothetical dietary patterns such as vegetarian, pescatarian, vegan, and flexitarian have been constructed to simulate the nutrient and energy content of typical diets, with varying intakes of plant and animal based foods. Potential effects on environmental impacts (e.g. greenhouse gas emissions) or inventories (e.g. land, water, or fertilizer use) have been calculated assuming the adoption of perceived sustainable and/or healthful dietary patterns. Some analyses have included predicted changes in health indicators such as mortality, diabetes, or cancer risk after adoption of these dietary patterns[27,28,29]. A recent publication by Springmann et al.[30] is the first to include estimated health effects of dietary choices based on the GBD dietary risk factors compared to certain environmental inventories (e.g. fertilizer, cropland, water use). However, no study has compared personal health effects with human health impacts of food production-related environmental effects using the same unit of measurement.

The work presented here is unique in two respects. Firstly, as proposed by Stylianou et al.[31], we have used DALYs[32] as a common unit to quantify and compare the environmental human health impact due to food production and the personal health impact of individual-level food consumption. In addition, we have evaluated other ecosystem relevant impacts on climate change, water scarcity footprint, and land-use related biodiversity loss. This approach allowed us to make a direct comparison between the environmental human health impacts of producing an individual's foods with the personal health benefits or potential harm from consuming the same foods. For example, from a global perspective, implementation of recommendations to increase vegetable intake to reach a certain minimum threshold to minimize personal disease risk only makes sense if the environmental human health impacts of this additional vegetable production does not lead to additional disease burden elsewhere. We have carried out such analyses not only for specific dietary risk factors (e.g. under consumption of vegetables or fruits), but also for total diets. Secondly, instead of assessing the potential health benefits and associated environmental impact reductions of theoretical sustainable and/or healthful diets, we applied our analytic approach to individual-level self-reported habitual food intakes for a European-wide dataset of 1457 persons (from the Food4Me Study[33,34]). This enabled us to link personal health impacts with environmental human health impacts of real diets at an individual level. Our analysis reveals the foods for which change in intake can have the biggest effects on both food production-related environmental impacts on human health and personal health consequences, and reveals the relationship between a healthful diet and its associated environmental impacts.

2. Methods

One goal of this work was to compare the environmental impacts of producing certain food types with the individual health impacts of under- or overconsuming the same foods. Figure 1 shows a general overview of how the environmental impacts (both human health and ecosystem based) and the personal health impacts of over and under-consumption of certain foods were calculated based on the Food Frequency Questionnaires provided by the Food4Me study[34]. The foods chosen for this assessment were selected from the food-based Global Burden of Disease (GBD) dietary risk factors (Table S1 and Figure 1) because under or over consuming these foods have been associated with personal health impacts[24]. There were three primary comparisons completed: 1) an individual's environmental human health impacts due to food production and their personal health impacts due to food consumption were compared with each other for each GBD dietary risk food category (i.e. environmental human health impacts of producing fruits compared to personal health impacts due to under-consuming fruits), 2) the environmental human health impacts of an individual's entire diet (the sum of foods in Figure 1 boxes A and B not just GBD dietary risk related foods shown in Figure 1 box A only) compared with an individual's total personal health impacts (the sum of personal health impacts due to all GBD dietary risk factors shown in Figure 3). Details of how each component was calculated are described further below and in the Supplemental Information (SI), and 3) comparing both the environmental human health impacts and personal health impacts to ecosystem based impacts (climate change, water scarcity footprint, and biodiversity loss) for each individual's total diet.

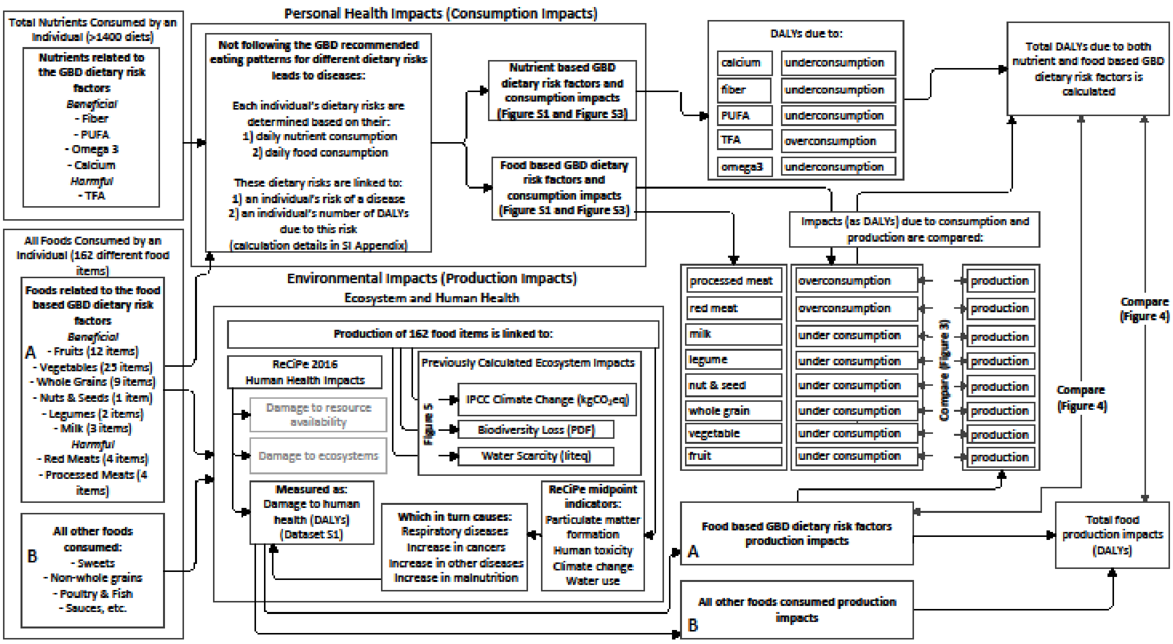

Figure 1. Flow chart for determining personal health (consumption) impacts and environmental human health (production) impacts based on an individual's recorded eating patterns. Items in gray indicate that they were not considered in this analysis. TFA is trans fatty acids, PUFA is polyunsaturated fatty acids, and µDALYs is micro disability adjusted life years. Calculation methods for the various methods are documented here: Recipe[15], Climate Change[53], Biodiversity Loss[50], Water Scarcity[16]

As mentioned above, the first analysis included only foods associated with the food based GBD dietary risk factors (Table S1, Dataset S1). In this case, GBD environmental human health impacts are the sum of each individual's impact due only to production of foods contained in each of the GBD food-based dietary risk factors. For example, for processed meat, environmental impacts associated with sliced cold meats, sausages, and bacon were summed according to the reported intake for each individual. In this case, any foods that were consumed that aren't considered in the risk factors (e.g. white meat), aren't considered in this analysis. Further details of the food items considered in each food group are included in Dataset S1. Foods not considered in this analysis were included in the other 'total diet' evaluation.

The GBD dietary risk factors also include personal health impacts due to under or over-consumption of certain nutrients (Table S1 and Figure 1). For these nutrients (omega 3, fiber, calcium, polyunsaturated fatty acids [PUFA], transfatty acids [TFA]), we calculated personal health impacts (Figure S3), but because there is no reliable method of calculating environmental human health impacts associated with production of individual nutrients, a comparison of nutrient-specific environmental human health impacts associated with the production of various food groups (cereals, breads, potatoes/rice/pasta, fruits, vegetables, dairy, meat/fish, soups /sauces, sweets, fats, drinks, or eggs) was completed and is included in the SI.

Estimates of individual food intakes were sourced from the baseline data collected from the pan-European study, Food4Me[34], which included 1457 adults of varying dietary patterns from seven countries (Germany, UK, Ireland, Netherlands, Poland, Greece, and Spain). The GBD Visualization Tool for the year 2016 was used to obtain the Western European DALY statistics for the health impacts[35]. A sensitivity analysis comparing the results of the Western European DALY statistics to the Global DALY statistics is included in the SI. Age based relative risks for the dietary risk-disease combination were based on the GBD estimates[24]. The ecoinvent 3.5 database[17], agri-footprint 4.0 database[36], and conversion factors to convert impacts from crop to product from Scherer et al.[37] were used for food production inventory data (Dataset S1). These databases provide global average inventories, not region specific, for crops and products, and therefore food transformation energy and transport distance impacts may vary based on a product's production versus consumption location. Global averages were used as region specific data, as well as product specific trade data, for many products is not readily available.

2.1 Personal Health Impacts from Food Consumption

DALYS due to personal health are calculated using the dietary risk factors identified by the Global Burden of Disease (GBD) study[24] as the index of healthfulness of dietary choices. The predicted personal health impacts for each individual due to their daily food consumption were calculated using several steps, and are also reported as microDALYs (µDALYs). For ease of understanding, results reported as µDALYs per day were extrapolated to DALYs incurred during an individual's lifetime using the following assumptions: 1) no changes were made to their eating patterns and 2) they followed these eating patterns over an 80 year lifetime.

Personal health impacts were calculated separately for each of the GBD dietary risk factor-disease combinations listed in Table S1 and shown in detail as risk-exposure relationships in Figure S1 based on a linear risk-exposure relationship as assumed in the method development in Stylianou et al.[31] and based on GBD's statement that a linear increase in the log of the relative risk exposure relationship is 'a reasonable approximation of the dose-response curve for many risks'[24]. Two dietary risk factors (diets high in sugar sweetened beverages and diets high in sodium) were not included because health consequences of these risk factors can depend on pre-existing individual conditions such as high body mass index or hypertension, respectively, rather than the quantity of food or nutrient consumed. The strength of the relationship between the dietary risk factor-disease combinations were characterized by the relative risk (RR), or the ratio of the probability of developing a disease when exposed to a certain risk factor (incidence proportion of disease in exposed population divided by incidence proportion in unexposed population), which, in the case of dietary risks, would be over or under-consumption of each GBD food or nutrient risk factor. The age dependent RR for each dietary risk-disease combination used here were provided in the GBD report[24] and are included in Dataset S2.

For each dietary risk factor, there is a recommended exposure level that would result in the lowest population disease burden, defined as the theoretical minimum risk exposure level (TMREL), that was developed by the GBD to minimize diet-related diseases[24]. For example, the GBD assumes that, while health benefits may increase with additional fruit intake, above 250 g/day of fruit intake, there are no reported or perceived additional health benefits. Therefore, 250 g/day of fruit is considered the TMREL (or recommended intake) for this dietary risk factor. These TMREL values were defined in the GBD study[24], and are shown in Table S1. The TMREL values in Table S1 represent either recommended minimum or maximum intake levels, depending on the food or nutrient, and, hereafter, are referred to as recommended intakes. A sensitivity to changing the TMREL values is included in the SI, as some reports[38] have suggested health benefits continue at higher fruit and vegetable intakes than the GBD suggests. The daily personal health µDALYs associated with each individual in the study were determined based on their reported consumption of the selected food or nutrient and on the relationship between dietary risk exposure (i.e. grams of food or nutrient consumed) and the µDALYs associated with this exposure, which are based on the age specific RR at a certain consumption level (e.g. Figure S1). One example calculation is included in the SI. Uncertainties for the daily personal health µDALYs were calculated using the GBD provided uncertainty values for each investigated disease and are shown in Dataset S2.

To translate the RR-exposure relationship to disease occurrence, the attributable fraction (AF) was calculated for each dietary risk-disease pair using Eq.1[39]. The AF provides the proportion of cases of each disease (j) that can be attributed to the specific dietary risk (under or overconsuming foods or nutrients) (i) being considered, based on the RR. This is necessary because each disease can be caused by various risk factors – not all can be attributed to diet alone. When several risk factors contribute to the same disease, there is a possibility that the sum of the AF for each risk factor can be larger than one, meaning that over 100% of instances of the diseases could have been prevented with the elimination of the known risks. This is due to joint effects of potentially correlated risk factors, which may be better estimated through a causal-web framework rather than a singular risk factor analysis. Given that this study focuses on dietary risk factors, it assumes that the AF for a specific disease would be eliminated only through removing the diet related risk factor, and does not include the effects of eliminating other risk factors that may have a causal interaction and influence avoidance of a particular disease (i.e. a risk of cardiovascular disease may be removed by reducing meat intake, but this may also be connected to smoking habits and low physical activity as well). Eliminating any of these factors may remove the risk of this disease, and the AF will change depending on the order these factors are removed[40]. This analysis assumes that the only removed risk factor for each specific disease is the dietary risk factor, and other potential risks remain constant. All RRs and AFs for each dietary risk factor-disease combination are included in Dataset S2.

$$AF_{i,j} = \frac{(RR_{i,j} - 1)}{RR_{i,j}} \quad \text{Eq. 1}$$

Following estimation of the AF for each dietary risk-disease combination, the number of DALYs associated with each disease (as provided by the GBD for Western Europe (WE)) for each dietary risk factor, per person per day, was calculated according to Eq. 2.

$$\frac{\mu DALYs_{i,j}}{person/day} = \frac{AF_{i,j} * \ WE\ disease\ specific\ \mu DALYs_j}{WE\ population/365} \qquad \text{Eq. 2}$$

The daily µDALYs associated with each individual in the study were determined based on their reported consumption of the selected foods and nutrients and on the relationship between dietary risk exposure (i.e. grams of food or nutrient consumed) and the µDALYs associated with this exposure (e.g. Figure S1).

Every individual's personal health impacts were calculated for each dietary risk-disease combination based on their eating patterns (Figure 3 and Figure S3). When clustering all dietary risk factors to calculate an individual's total personal health impacts (i.e. personal health impacts from all dietary risk categories combined), Eq. 3 was used to calculate the combined AF_j per disease, as AF for combinations of risk factors all contributing to the same disease are multiplicative and independent[41]. After calculating the combined AF_j per disease due to all combined dietary risks, Eq. 2 was used to calculate the disease specific µDALYs per person per day, and these estimates were summed to calculate an individual's total daily µDALYs due to all diseases associated with their consumption patterns.

$$AF_j = 1 - \prod_{0}^{i}\left(1 - AF_{ij}\right) \quad \text{Eq. 3}$$

2.2 Environmental Impacts from Food Production

The environmental impacts due to the production of each individual's daily food intake were calculated based on their baseline recorded food consumption[33,34], using a 162 item food frequency questionnaire (FFQ), of each person taking part in the Food4Me Proof of Principle intervention study[33,34]. Emissions and resources used to produce one gram of each of the 162 food types in the FFQ were calculated based on the inventory data of Walker et al.[42] in combination with the food production inventory databases mentioned above. System boundaries for the inventory analysis included production, transport, and storage of the raw and processed food items based on the ecoinvent 3.5 inventories and system boundaries, with details of inventory assumptions and each food item's final environmental human health impacts detailed in Dataset S1. For food requiring energy for further processing not considered in the ecoinvent database (breakfast cereals and processed meats), further processing impacts were not included. This was done to ensure that dietary risk categories were evaluated under similar conditions to each other – in some categories foods can be consumed either raw or processed, and cooking may be done in a factory or home setting (or both) depending on an individual's preferences. In addition, some categories (e.g. whole grains) include food items with fairly different processing requirements. Whole grain bread, baked in a factory setting, could have different processing methods and impacts than brown rice, which would most likely be cooked at home. In order to avoid the variability in cooking locations, methods, and personal preferences, this factor was not included in the analysis. The energy use to additionally process these foods can range from 6.1 Megajoules (MJ) per kg of food (breakfast cereals)[43] to 12.1 MJ per kg food (processed meats)[44] and include a combination of heat energy and electricity depending on the processing (details of additional processing impacts are in Walker et al.[42]). Given that global electricity environmental human health impacts per MJ of energy are 1.14E-5 DALYs, environmental human health impacts of food items requiring energy intensive processing may be underestimated.

For the assessment of environmental human health impacts, the LCIA method Recipe 2016 version 1.1 Endpoint Egalitarian version for human health[45] was used. This method was chosen as it has been recently updated, is applicable on a global scale, and is easily calculated (with uncertainties) using the SimaPro[46] software. In Recipe, particulate matter formation, ozone formation, ionizing radiation, stratospheric ozone depletion, human toxicity (separated by cancer and non-cancer causing disease risk), climate change, and water use lead to the following damage pathways to human health: increase in respiratory disease, increase in cancers and other diseases, and increases in malnutrition, malaria, and diarrhea, as well as increased flood risk. The sum of the impacts of these damage pathways are quantified into a final category – damage to human health, which is measured using DALYs. In the case of human health damage due to climate change, regional affects were summed for a final total effect[47], which led to a total of 1.25E10-5 DALYs per $kgCO_2$ equivalents. Stratospheric ozone depletion is responsible for increases in DALYs due to increasing the rates of skin cancer and cataracts with increasing amounts of kg CFC-11 equivalents. Different pigmentation levels at different longitudinal zones were taken into account to calculate the incidence of skin cancers, with a final value of 1.34E-03 DALY/kg CFC-11 equivalents used to calculate the human health impacts[15]. Ionizing radiation, which is caused by anthropogenic emissions of radionuclides due to human activities such as mining, nuclear fuel cycle, and coal burning, can cause many types of cancers and is measured as kBq Co-60 to air equivalents. A final value of 1.4E-08 DALYs/kGb Co-60 emitted to air equivalents was used to calculate DALYs[15]. Both primary and secondary aerosols exposure, measured as particulate matter formation potential, can cause respiratory problems, with a final conversion factor of 6.29E10-4 DALYs/kilogram PM2.5 equivalents[15]. Photochemical ozone formation, with a conversion factor of 9.1E-7 DALYs/kg NOx-equivalents, can affect human health through inflamed airways and damaging lungs, leading to increased instances and severity of respiratory diseases[15]. Human toxicity calculations are based on the fate, exposure, and effect of a chemical, and in Recipe are based on the global multimedia fate, exposure and effects model USES-LCA 2.0. All exposure routes were considered (air, drinking, food, and water), and toxicity potential was expressed as kg 1,4 dichlorobenzene-equivalents (kg 1,4-DCB eq) for all included chemicals. Human toxicity (cancer) was taken as 3.32E-06 DALY/kg 1,4-DCB eq and human toxicity (non-cancerous) is 6.65E-09 DALY/kg 1,4-DCB eq[15]. In the case of water use, a reduction in freshwater availability that prevents irrigation can lead to malnutrition and the vulnerability of the population, measured by a human development factor and per-capita water requirements to prevent malnutrition. Final human health impacts were measured by 2.22E-06 DALYs/cubic meter of water based on the global average for country specific consumption-weighted human health characterization factors[15]. Details of the calculation methods, assumptions, and midpoint and endpoint characterization factors developed behind these values are explained in detail in the Recipe documentation[15] and will not be discussed here. These environmental health impacts due to food production may not be felt directly by the person consuming the food, but are distributed regionally and globally e.g. through particulate matter emissions or climate change effects resulting from the food production[48]. One example calculation is included in the SI.

There is always a high degree of uncertainty in the calculation of environmental human health impacts due to food production. In the Recipe life cycle assessment methodology[15], impacts are first calculated at the midpoint level and then aggregated to an endpoint value. In the case of the effects of climate change on human health, for example, midpoint impacts are calculated for six categories using different units (global warming [$kgCO_2$ equivalents], stratospheric ozone depletion [kg CFC11 equivalents], ionizing radiation [kBq Co-60 equivalents], ozone formation [kg NO_x equivalents], fine particulate matter formation [kg $PM_{2.5}$ equivalents], and human toxicity [kg 1,4 DCB]). These are then aggregated into a final endpoint value, measured in the unit of DALYs, based on various factors. There is uncertainty in both the midpoint calculations (i.e. the lifetime of CO_2 is measured by the effectiveness of mitigation, which varies according to different climate models), and the conversion of midpoint values to an endpoint value (i.e. the effect of global warming [$kgCO_2$ equivalents] to human health impacts [DALYs] is highly dependent on the species ability to adapt to the varying conditions). Uncertainties of environmental human health impacts for each food item were analyzed using the Simapro[46] software and are included in Dataset S1.

The impacts of each gram of food have also been previously calculated for climate change, water scarcity footprint, and land-use driven biodiversity loss[42]. Climate change impacts (measured as $kgCO_2$ equivalents) were calculated using Brightway[49] and the IPCC 100 year GWP characterization factors using a combination of the food production inventory databases mentioned above. Water scarcity footprint (liter equivalents) used global production-weighted water footprints per crop[16] based on monthly, regional water stress indexes. Biodiversity impacts (measured as potentially disappeared fraction (PDF) of species*years) also used global production-weighted average biodiversity loss per crop[50] based on the percentage of global species that are lost at through land use. For both water scarcity footprint and land-use biodiversity loss, impacts associated with livestock production (beef, chicken, milk, eggs, pig, sheep, and fish) were based on the cultivation of animal feed and pasture land required[51,52]. Further details of these impact calculations are available in Walker et al.[42] Figure 1 shows that ecosystem based environmental impacts were calculated in a previous assessment, and are included as a comparison to the environmental human health and personal health impacts calculated for this analysis. For the calculation of the environmental human health impacts in Recipe there are some redundancies to the previously calculated ecosystem impacts – for example the IPCC GWP climate change calculations are also incorporated into the Recipe human health impacts as a measure of damage climate change can cause to human health, as discussed above.

As a summary, to produce food for each individual's diet, impacts from several environmental impact categories were calculated:

1. *Environmental human health impacts*: Human health impacts to produce food, measured in DALYs
2. *Environmental or ecosystem impacts*: Climate change, water scarcity footprint, and biodiversity loss to produce food, measured in kgCO2equivalents, liter equivalents, and PDF species*year, respectively

Each individual's diet consists of three subcategories:

1. *Food group specific impacts*: Refers to the environmental impacts associated with specific dietary risk categories (each item in Figure 1 box A)
2. *Total diet production impacts*: Refers to the sum of each type of environmental impact associated with ALL food consumed by an individual (Figure 1 sum of boxes A and B, Dataset S1)
3. *GBD dietary risk factor environmental impacts*: Refers to the sum of each type of environmental impact for all foods associated with the GBD food based dietary risk factors (seeds/nuts, vegetables, whole grains, fruit, legumes, milk, red meat, and processed meat – Figure 1 box A, Dataset S1).

3. Results

3.1 Daily recorded eating patterns and intake-related health impacts

Intakes of various food groups, their comparison to recommended intakes and their impact on DALYs for the sample population investigated is presented in Figure 2, with blue lines indicating the mean values and the violin plots showing the distribution. Figure 2a shows the percentage of over or under consumption across the study population (100% line) for each dietary risk factor. Figure 2b and d are separated for better visualization due to the near zero recommended intake and indicates the grams rather than percent consumed. Areas in red indicate that there is risk for disease at this consumption level, and areas in green indicate that there is no risk for disease at this consumption level. Figures 2c and d show the years of life lost (Disability Adjusted Life Years) for each of the dietary risk factors across the study population, assuming that the reported diets are consumed over the complete lifetime. Details of the specific foods from the Food Frequency Questionnaire that are included in each dietary risk category are provided in Dataset S1. Numbers under the dietary risk factors indicate the maximum or minimum recommended intakes. Intakes of vegetables, legumes, milk, seeds/nuts, poly unsaturated fatty acids (PUFA) are on average under-consumed, i.e. they do not meet recommended intakes (Figure 2a), and therefore have an impact on personal health DALYS due to higher risk of disease associated with low consumption (Figure 2c). The largest DALYs are from seeds/nuts, vegetables, and then whole grains. Low-consumption of milk was associated with very few personal health DALYs. Red and processed meat are both overconsumed with respect to recommended intakes, with processed meat associated with more personal health DALYs than red meat across the study population.

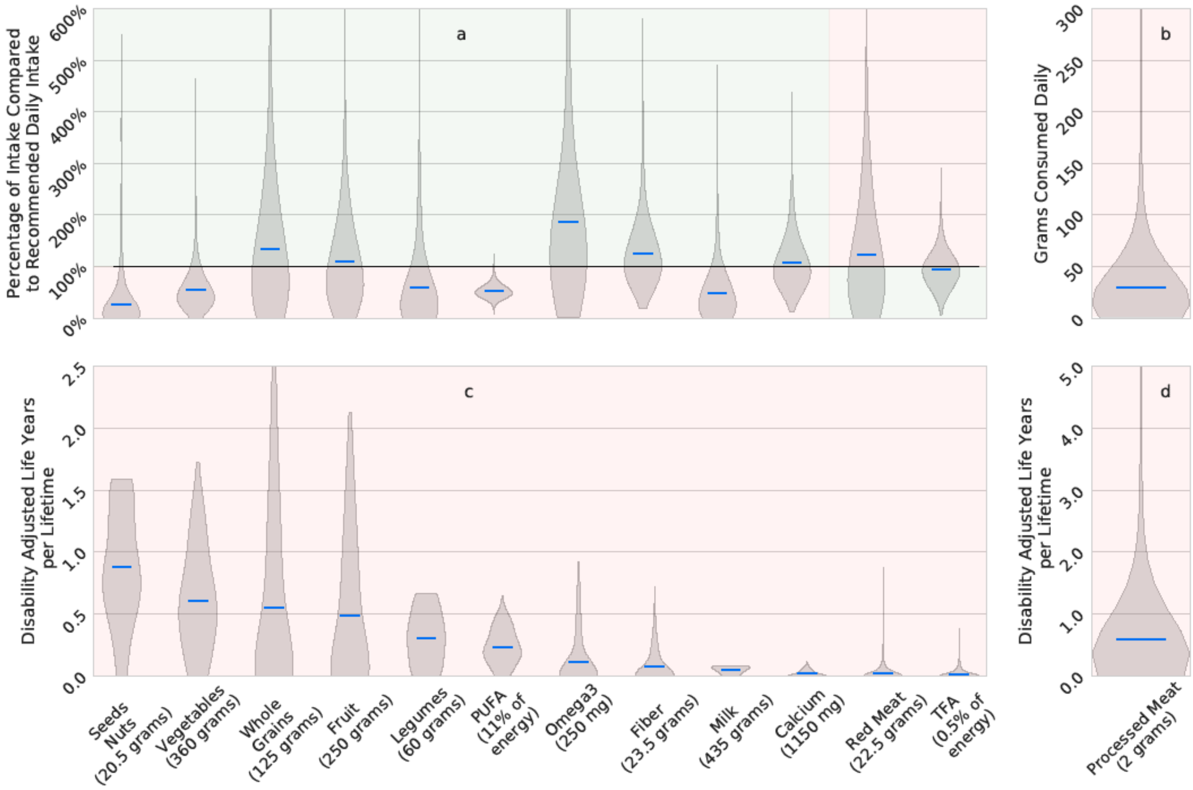

Figure 2. The shape of the violin plots shows a rotated kernel density plot representing the sample distribution, with the thickness of the shape showing how common a particular value was. Blue lines indicate the mean values. Figures 2a and b show intakes of dietary risk factors for the study population compared with daily theoretical risk exposure limits (GBD recommended intakes). Figures 2c and d show the years of life lost (Disability Adjusted Life Years) for each of the dietary risk factors across the study population, assuming that the reported diets are consumed over the complete lifetime. Numbers under the dietary risk factors indicate the maximum or minimum recommended intakes. PUFA is poly-unsaturated fatty acid and TFA is trans-fatty acid.

3.2 Relationship between Personal Health Impacts (from food intake) and Environmental Human Health Impact (from food production) for Specific Dietary Risk Factors

In our first analysis, environmental human health impacts (Figure 3 x-axis) and personal health impacts (Figure 3 y-axis), both measured in terms of lifetime DALYs, were compared for each of the dietary risk factors separately (e.g. grains, fruit, nuts, milk). Each point represents the impact results for each individual taking part in the dietary survey, and shading indicates the mass of food consumed for each dietary risk factor over a lifetime of consumption. Dietary risks are divided into two categories (encouraged foods (for which higher intakes have health benefits) outlined in a solid green line and discouraged foods (for which higher intakes are considered detrimental to health) in a solid red line). In some cases, environmental and personal health impacts are positively correlated, for example, as consumption of red and processed meat increases, both the environmental and individual health impacts increase (Figure 3 'Discouraged Foods'). This suggests that both environmental and health impacts would be reduced by reducing red and processed meat consumption. However, in other cases, this relationship is negatively correlated, for example, higher consumption of fruit decreases an individual's personal health impacts up to the point that the recommended intake is met. Above that point there is no further change in personal health impact but environmental human health impacts, associated with increased production demand, continue to rise. Food groups that consist of a wide range of food items (such as vegetables) have a larger variation of environmental human health impacts associated with their production, which is responsible for the wider distribution of data points when compared to singular items such as milk. The Impact Ratios in Figure 3 show the lower, average, and upper limits of the strength of the relationships between the environmental and personal health impacts for each of the dietary risk factors based on uncertainties in the data. The Impact Ratio ranges are calculated based on the lowest or highest potential environmental human health impacts (based on the SimaPro[46] uncertainty analysis data shown in Dataset S1) in combination with the lowest or highest calculated consumption impacts (based on the GBD DALY ranges[35] for each disease shown in Dataset S2). These numbers represent the change in personal health DALYs for every 1 DALY increase in environmental human health impacts associated with production, up to the point where intake meets the recommendation. The relationship is particularly strong for whole grains and legumes, where, respectively, personal health impacts of 7.7 (5.7 to 10.4) and 7.2 (5.1 to 13.1) DALYs could be avoided if recommended intakes are met, at the cost of a 1 DALY increase in environmental human health impacts due to increased production. Processed meat has a strong reinforcing relationship – a 1 DALY production increase is associated with an increase of 1.2 (0.9 to 1.9) personal health impact DALYs. The relationship for red meat is not as strong, because although there are higher environmental human health impacts associated with production, there are lower health risks due to over consumption when compared to processed meats, due to differing nutrient content. In the case of vegetables, personal health impacts and environmental human health impacts are similar at around 250 grams of intake (Figure S3). The environmental and personal health impact relationship is weak for milk because of the combination of a relatively low disease risk due to under-consuming milk (based on the reported 2016 GBD relative risk values), in combination with relatively high production impacts. However it should be noted that more recent epidemiological and intervention studies regarding dairy consumption showing varied results and long term impact on health needs to be more fully elucidated.

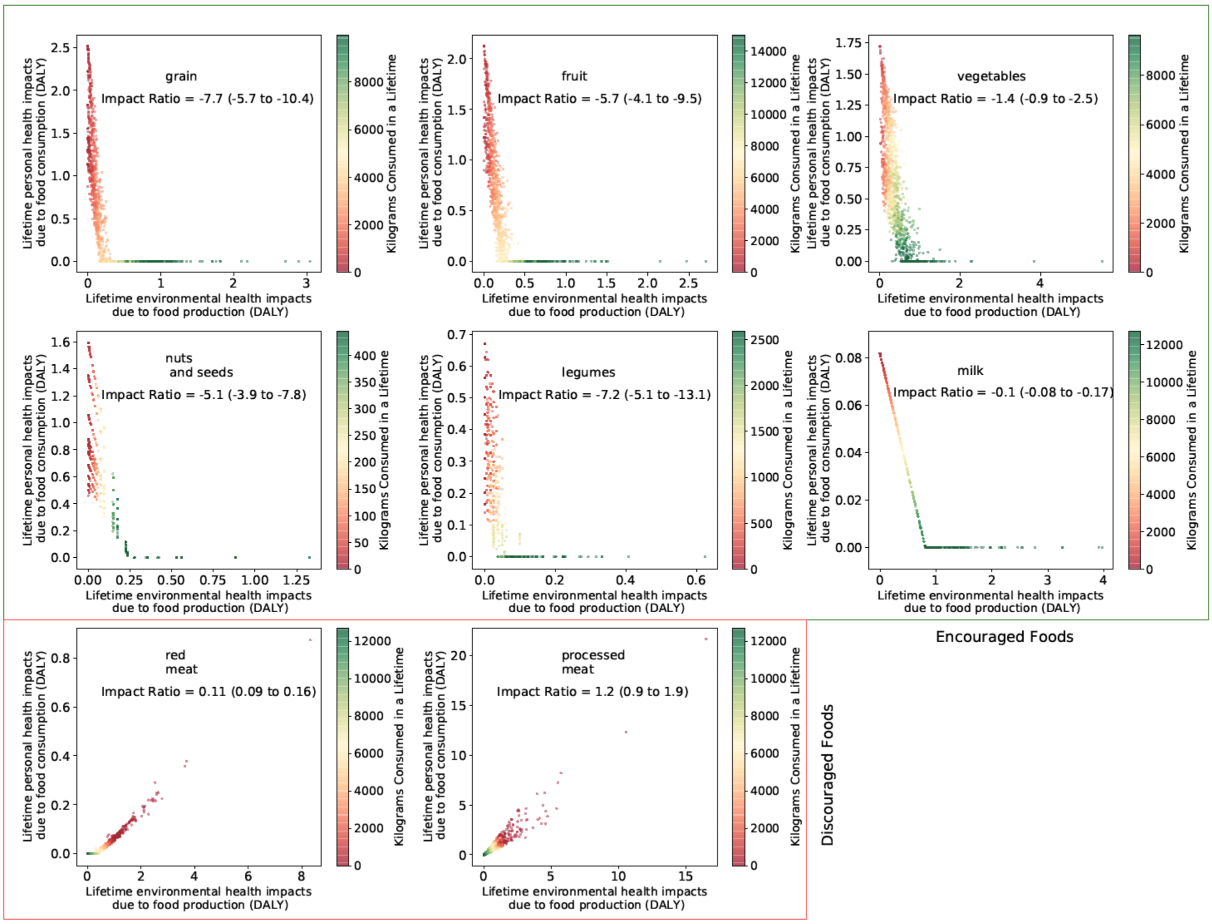

Figure 3. Lifetime DALYs for each individual (each individual is represented by one dot all graphs) for each dietary risk (1 sub-graph per risk factor) due to environmental human health impacts associated with food production (x-axis) and personal health impacts due to food consumption (y-axis). Color shading of dots represents the kilograms of food consumed for each dietary risk factor. The Impact Ratios under each dietary risk factor indicates the minimum, average, and maximum strength of the

relationship between environmental and personal health impacts, i.e. the average change in personal health DALYs for each 1 DALY increase in environmental human health impacts due to additional production. Dietary risks are divided into two categories (encouraged foods (for which higher intakes have health benefits) outlined in a solid green line and discouraged foods (for which higher intakes are considered detrimental to health) in a solid red line).

This analysis assumed that there is no added disease risk reduction in consuming encouraged foods above the recommended intake values, however some studies[38] have found that there may in fact be some benefits to consuming intakes higher than the GBD recommended intakes. For this reason a sensitivity analysis changing the recommended intake levels was also conducted. These changes resulted in only slight changes in the consumption and production DALY slopes, with detailed results given in the SI. For details as to how the environmental and personal health impacts relate to grams of food consumed rather than to each other per dietary risk, refer to Figures S1, S2, and S3. An additional analysis investigating the environmental human health impacts associated with nutrient production for various food groups (e.g. dairy, grains, meat, sweets) is included in the SI. The findings show the food groups that can provide a specific nutrient with the lowest production impacts. As an example, eggs are the lowest impact food providing omega 3. The lowest impact food to provide calcium and fiber is bread. While dairy is a concentrated source of calcium, its high production impacts compared to bread mean it is not the lowest impact way of obtaining calcium in a diet.

Reducing red and processed meat intake will provide the highest environmental human health impact reductions, and increasing nut/seed and vegetable intakes will provide the largest personal health benefits (Table 1). In terms of other evaluated environmental impact categories (climate change, water scarcity footprint, and biodiversity loss), reducing red and processed meat will still offer high impact reductions, as these food items have particularly high impacts in all evaluated impact categories. While increasing nut/seed consumption provides high health benefits, it does not have a large environmental human health impact associated with this increased consumption (Figure 3). It may, however, have a large impact on an individual's water scarcity footprint, particularly if the increased consumption is provided by almonds, which have relatively high water scarcity impacts compared to climate change, biodiversity, or environmental human health impacts[16]. Similarly, fruits and vegetables typically grown in water scarce regions (e.g. olives) may have low environmental human health, climate change, and biodiversity loss impacts, but have high water scarcity footprints. Increasing legume intake (or intake of any fruit or vegetable sourced from a tropical region) will improve an individual's health, but these items tend to have high biodiversity loss impacts relative to climate change and environmental human health impacts. Details of individual food items contribution to other environmental impact indicators can be found in a previous publication regarding this sample population[42].

Table 1. Average DALYs for the sample population per person per lifetime based on recorded eating patterns for both environmental human health impacts and personal health impacts, shown from highest to lowest. Standard deviation among the population indicated. Sum of environmental human health impacts only includes food items associated with the GBD dietary risk factors (details in Figure 1 box A) shown in the table (for total impacts including foods falling outside of the GBD dietary risk categories see Figure 4 and Figure 1 boxes A and B). Total of personal health impacts was calculated by clustering the dietary risk factors assuming multiplicative attributional fractions, as described in the Methods, and is therefore not simply the sum of the personal health impacts associated with each dietary risk.

Environmental Human Health Impacts (due to production)	**Personal Health Impacts (due to consumption)**
Measured as average DALYs per person per lifetime based on recorded eating patterns of the sample population	
Processed Meat: 0.55 ± 0.52	Nuts and Seeds: 1.0 ± 0.52
Red Meat: 0.48 ± 0.52	Vegetables: 0.76 ± 0.51
Milk: 0.41 ± 0.45	Whole Grains: 0.70 ± 0.9
Vegetables: 0.36 ± 0.3	Processed Meat: 0.64 ± 1.09

Whole Grains: 0.29 ± 0.31	Fruit: 0.60 ± 0.72
Fruit: 0.26 ± 0.23	Legumes: 0.35 ± 0.25
Nuts and Seeds: 0.06 ± 0.12	Milk: 0.02 ± 0.01
Legumes: 0.03 ± 0.04	Red Meat: 0.02 ± 0.04
SUM: 2.4 ± 1.3	**SUM: 2.5 ± 0.9**

3.3 Relationship between Personal Health Impacts (from food intake) and Environmental Human Health Impacts (from food production) for Total Diets

A second analysis was done for each individual's total diet. Total diets include all foods consumed, not just those associated with the GBD dietary risk factors. All study participants consumed foods that are not included in the food-based GBD dietary risk factors, such as non-whole grain foods, sweets, sauces, beverages, and white meat (Dataset S1 and Figure 1 box B). The environmental and personal health impacts of the many foods outside the panel of food-based GBD dietary risk factors were not considered in Figure 3 or Table 1. Environmental human health impacts due to their total food production were compared to their total personal health impacts, independent of the dietary risk category.

Given that the GBD was concerned with dietary risks for which there is reliable evidence of high potential for individual health consequences, it is likely that the inclusion of these other foods will have limited influence on an individual's total personal health impacts. However, these other foods do have environmental human health impacts associated with production that have not been considered. Figure 4 shows each individual's environmental human health impact for the food production associated with their total diet (colored red and detailed in Dataset S1 and Figure 1 - sum of foods in boxes A and B) and the food production associated only with the foods included in the GBD dietary risk factors (colored blue and detailed in Dataset S1, Figure 1 box A). On average, the average environmental human health impact for all food consumed over an individual's lifetime was 5.8 ± SD 2.4 DALYs per person (200 ± SD 83 µDALYs per person per day) and of this total approximately 41% (SD ± 11%) was due to foods associated with the GBD dietary risk factors. We found that when comparing either a person's total diet environmental human health impact (Figure 4 x-axis red points), or the environmental human health impacts of foods associated with the GBD dietary risks (Figure 4 x-axis blue points), to their total personal health impact (Figure 4 y-axis), there is very little correlation between the two variables. This means that healthier dietary patterns (i.e. those with lower personal health impacts) are not necessarily associated with lower or higher environmental human health impacts. Individuals who had both low environmental and personal health impacts (in the lower third of the sample population for both) consumed 25% more cereals, 21% more fruit, and 17% more vegetables than the average study population and they consumed lower than average amounts for all other food groups (ranging from 24% less soups, sauces and spreads to 53% less meat and fish). These results correlate well with our past findings from this same sample group[42], in which nutrient deficiencies (too little of certain vitamins or minerals) or nutrient overconsumption (too much of sugars, saturated fats, or sodium) and their relation to climate change, water scarcity footprint, and land use based biodiversity loss were analyzed. The past findings found that to achieve a low environmental impact, high quality diet, individuals should consume more cereals and vegetables and decrease meat, drinks, and sweets intake.

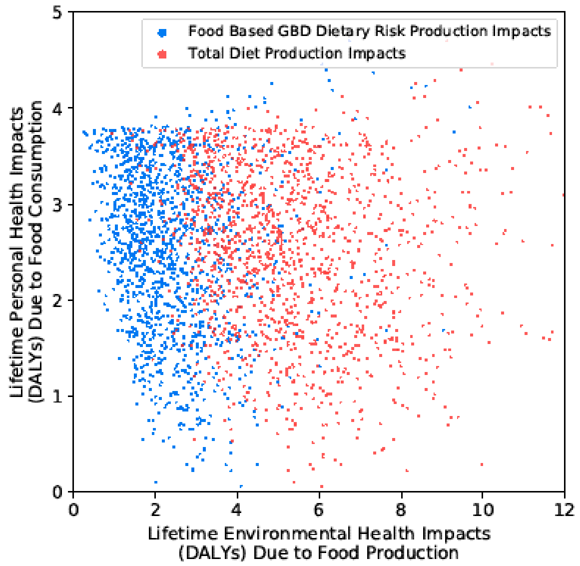

Figure 4. Personal lifetime total health impacts (as DALYs) as they relate to the environmental human health impacts of their total diet (red), which includes all foods consumed by a person per day, and of the environmental human health impacts of GBD dietary risk factor foods only (blue), which includes the sum of the impacts of foods falling in the following food categories: whole grains, fruits, vegetables, red and processed meat, milk, legumes and nuts/seeds.

Total personal health impacts were also compared to each of the ecosystem relevant environmental impact categories described below. As was observed in Figure 4 between environmental human health impacts and personal health, there was little correlation between the food intake-related personal health impact and the environmental impacts (SI Figure 5a through d), although it has been found that diets following the national recommendations can be associated with lower greenhouse gas emissions depending on the national income level[46]. Results, along with other nutrition indicators that were evaluated in our previous publication[42], are shown in the SI. It was observed that as total personal health impacts increased, an individual tended to consume fewer beneficial nutrients (SI Figure S5e). People avoiding five or more GBD dietary risk factors tended to have nutrient adequacy ratios of > 0.97 (out of 0 to 1.0, with 1.0 indicating average adequate nutrient intakes for their age and gender), whereas people avoiding less than three GBD dietary risk factors tended to have nutrient adequacy ratios of 0.89 to 0.93. The relationship was less established for the intake of harmful nutrients (SI Figure S5f).

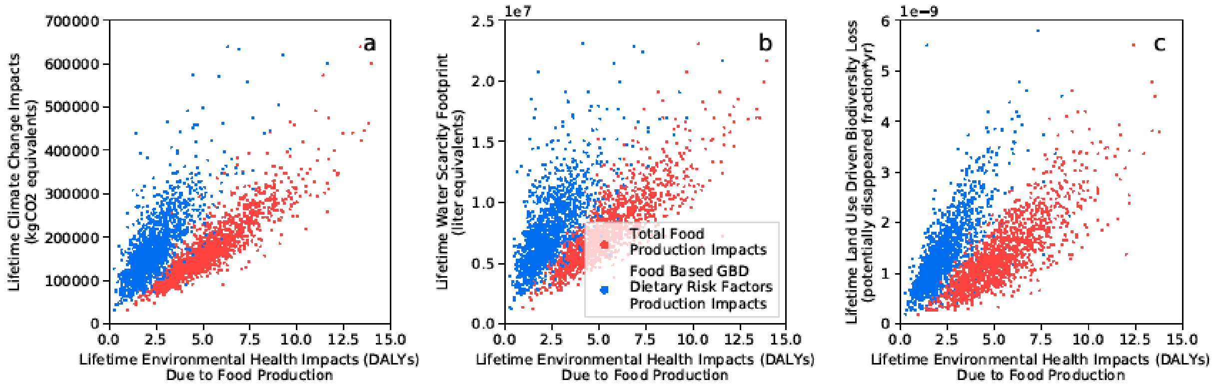

Figure 5. The relationship between each individual's environmental human health impacts as DALYs per lifetime (x-axis) and their environmental impacts per lifetime measured as a) climate change (kgCO_2 equivalents), b) water scarcity footprint (liter equivalents), and c) land use driven biodiversity loss (potentially disappeared fraction*years). Red points show the total production DALYs (total diet) and blue points show the sum of food-based GBD dietary risk factor production DALYs.

3.4 Relationship between Environmental Human Health Impacts (from food production) and Other Environmental Impacts (from food production)

A third analysis comparing the results of the environmental human health impacts to ecosystem relevant impact categories (climate change[53], water scarcity footprint[16], and biodiversity loss[50]), which were calculated in our previous publication investigating this sample population[42], was conducted. There are positive correlations between environmental human health impacts and ecosystem relevant impacts (Figure 5) for food production, indicating that a reduction (or increase) in environmental human health impacts due to changes in food consumption will likely correspond to a reduction (or increase) in other environmental damage categories. Figure 5 shows the impact of each individual for both their total diet (all foods consumed – red points) and their diet including only foods considered in the GBD dietary risk categories (blue points). In the case of climate change (Figure 5a), this relationship is relatively strong (r^2=0.82), as the environmental health impacts calculated by Recipe[15] include the human health impacts due to climate change. For water scarcity footprint (Figure 5b) and biodiversity loss (Figure 5c) (r^2=0.74 and 0.71, respectively) the correlation is weaker, as there are relatively high biodiversity impacts associated with foods produced exclusively in tropical regions (e.g. chocolate or coffee) and relatively high water scarcity impacts with crops that tend to be produced in water scarce regions (e.g. olives or almonds).

Environmental impacts were calculated using global food production weighted averages, when available, in order to provide identical baseline data on which environmental and personal health impacts across the sample population could be compared. This was done intentionally to focus on the links between dietary choices and environmental impacts. Food purchasing habits (e.g. food production methods, location, and season), however, could additionally influence the magnitude of impacts for similar foods.

4. Discussion

As expected, we found that for red and processed meat, reducing consumption reduces both environmental and personal health impacts due to their relatively high environmental human health impacts for production and potentially detrimental health consequences from consumption. For the other GBD dietary risk factors, however, increasing consumption of seeds/nuts, whole grains, fruit, and legumes are predicted to produce measureable health benefits for those who currently under-consume these foods, while only adding slightly to environmental human health impacts associated with production, meaning there are clear benefits to increasing these intakes to recommended levels. We found that milk was unique in that environmental and personal health impacts were relatively equal – the health benefits of increasing intake were offset by the impacts required to produce this intake, and this should be taken into consideration in future dietary recommendations. Recommendations to increase vegetable intakes are beneficial to personal health, however the environmental human health impacts associated with this increased production may exceed the personal health benefits. The dietary risk factors not investigated (sugar sweetened beverages and sodium) are expected to follow similar patterns to the meat risk factors, however with significantly lower environmental human health impacts associated with production. In addition, results show that overall healthier diets, as defined by the GBD dietary recommendations and quantified by low personal health DALYs, were not necessarily associated with lower environmental impacts, whether measured through human health impacts, climate change, water scarcity footprint, or biodiversity loss. It should be noted that while personal health impacts affect the individual, environmental human health impacts, particularly localized impacts such as toxicity, may be outsourced to the food producers and suppliers.

The study is unique in that it uses a dietary dataset from >1400 European adult participants in the Food4Me Study to calculate environmental impacts and personal health impacts of real diets, with all the associated nuances, rather than the hypothetical diets (e.g. vegetarian, vegan) typically used in evaluating environmental impact reduction potentials as they compare to health effects[25]. The Food4Me Study is valuable in that it provides a robust dietary dataset for adults of both genders who are broadly representative of the European population with respect to geography, health status and food consumption patterns[34]. This allows for consistent dietary data collection and boundary conditions that can be lacking in environmental assessments between populations[54]. Health data and food production data can be derived for each individual, allowing for a direct comparison of the two variables using identical units (DALYs), which hasn't previously been done in total diet research comparing environmental and health impacts.

This discussion focuses on the diets of Europeans, however a similar methodology can be easily applied globally or to a specific country as long as dietary data is available. Detailed consumption data, often available for more developed countries, can provide the most accurate results both in terms of environmental human health impacts and personal health impacts, but at a minimum total consumption of foods in each of the dietary risk categories (i.e. nuts and seeds, processed meats, etc.) is required. Country specific GBD data is already available. Results may vary depending not only on a country's typical food consumption patterns (i.e. high meat or low vegetable intakes), but also among socio-economic categories, which often affect dietary choices[46].

There are several limitations to the analysis of personal health impacts. One is isolating the effects of dietary habits from other environmental and lifestyle factors e.g. physical activity or genetics in each's contribution to specific diseases. Limited physical activity[55], unbalanced energy[56], and genetic factors [57,13] all contribute to the aetiology of obesity, which is a major risk factor for most common non-communicable diseases. The epidemiological studies that have been used in the GBD have adjusted for age, sex, and other potential risk factors to isolate the effects of the dietary risk factor on the disease, however there may be other, yet unknown, confounding variables that prevent absolute isolation of the effects of other environmental, behavioral, and hereditary factors that may influence the relative risk (RR)-exposure relationship. One example of a dietary confounding factor is the tendency for people eating large amounts of meat to consume lower amounts of fruits, thus overestimating the RR for the specific risk-disease relationship being evaluated[58]. To quantify the effects of potential confounding variables in dietary patterns, an internal validation was undertaken by the GBD that compared the effects of the risk of a singular risk-disease combinations to the estimated effects of the risk of various typical dietary patterns and found that the effects of dietary patterns compared to single dietary risks was insignificant (estimated RR to measured RR was 0.98 to 1.0)[41]. An additional limitation in the epidemiological studies can come from grouping various types of foods together into similar groups (e.g. fruits, vegetables, nuts/seeds), regardless of the differing nutritional quality that may exist between, for example, an orange and an apple. It has been found that varying the variety of foods within food groups leads to better nutritional adequacy[59], and this study does not take into account how limited variety within a food group can affect the results, even if adequate amounts of the food group are consumed.

This analysis did not include the possible impacts on both short- and long-term human health due to consumption of pesticide residues in foods[60,61]. For example, consumption of organic produce rather than conventionally-produced foods may lower risks for both pesticide and drug-resistant bacteria intake[62]. Within the European Union 97% of tested foods had residue values within the legal limits permitted[63], so the health effects from pesticide (or other contaminant exposure), for European adults, is likely very limited, and thus its exclusion from the present analysis is justified. Other research has estimated that the pesticide related personal health impacts of typical fruit and vegetable consumption in Switzerland equates to an additional 8.6E-06 DALYs/person/lifetime[64]. Compared to the lifetime personal health DALYs due to under-consumption of fruits and vegetables (an average of 0.61 and 0.48 DALYS/person, respectively, shown in Figure 2c), the effects of residual pesticide consumption is essentially insignificant. While the overall influence of including pesticide ingestion in the assessment is not expected to be substantial in view of these findings, for the sake of completeness future research should include pesticide ingestion through food and also tradeoffs with production impacts. For example, reducing pesticide use may correlate with lower crop yields, and thus influence other environmental impact categories such as land use and biodiversity loss.

While dietary recommendations are targeted to the population to achieve better health through an improved diet, these recommendations are also associated with health damage due to production.

Personal health benefits may not outweigh the overall environmental impacts associated with production of the recommended food intakes, however the strength of this relationship varies among different food groups. In addition, there is a common misconception that healthful diets tend to be associated with lower environmental impacts. Based on the recorded real diets across Europe, and using the GBD dietary risk factors as an indicator of healthful diets, this was not the case.

The authors declare that there are no competing interests.

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Data Availability

Data used in this assessment is attached as two dataset excel files. Each individual's personal information such as recorded daily food consumption, gender, age, and location is not available.

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Supplemental Information for

Comparing environmental and personal health impacts of individual food choices

Christie Walker, Eileen R. Gibney, John C. Mathers, Stefanie Hellweg

Christie Walker
Email: walker@ifu.baug.ethz.ch

This PDF file includes:

Supplementary text
Figures S1 to S5
Tables S1 to S3
References for SI reference citations

Other supplementary materials for this manuscript include the following:

Datasets S1 to S2

Dietary Risk Factors

Below are the details of the types of foods included in each dietary risk category. Further details are included in Dataset S1. Table S1 shows a list of the dietary risks, diseases associated with under and over consumption, and the recommended daily intakes.

Low whole grains: In order to calculate the daily amount of whole grains consumed by each individual in the study whole meal breads and pastas, brown rice, porridge, muesli, crispbreads, whole grain breakfast cereals, and brown breads and rolls were considered. Items like white breads, white rice, and non-wholegrain breakfast cereals were excluded.
Low fruit: Fruit consumption values included whole fruits, dried fruits, and canned fruits and excluded fruit juices, salted, or pickled fruits.
Low nuts and seeds: The daily consumption of nuts and seeds was available from the study data, however the types of nuts and seeds consumed was not specified. The production impacts were taken as an average of almonds, peanuts, and sunflower seeds because of limited data availability.
Low vegetables: Vegetable intake was calculated as the total whole vegetable consumption excluding legumes and starchy vegetables such as potatoes and corn.
Low legumes: Legume intake was calculated as the total legume consumption and included both baked beans and dried beans as they were recorded in the FFQ survey. Dried bean intake as measured in the food frequency questionnaire was multiplied by two to account for their weight as they are consumed.
High processed meat: For this study, processed meats were considered to be any meat that was cured or smoked, such as sliced cold meat, sausages, and bacon.
Low milk: For this study, any low-fat, skim, or full fat milk was considered in the consumption volume. Any form of cheese, yogurt, were not considered in this category, but rather in the calcium dietary risk category, as calculated by the Global Burden of Disease (GBD)[1].

High red meat: An individual's consumption of red meat included any beef or venison, burgers or meatballs, and any source of offal or pate.

Table S1. Dietary risk factors, associated diseases, changes in consumption, and either maximum or minimum recommended intake levels (TMREL) as defined by the GBD[1]. Changes in consumption refer to the GBD defined changes for food intake in each dietary risk factor that will result in a change in the relative risk (RR). Age specific relative risks and attributional fractions for each dietary risk – disease combination are included in the Dataset S2.

Dietary Risk Factor	Diseases	Change in Consumption that results in a change in the relative risk (RR)	TMREL (Recommended Daily Intake Values)
Food Based Dietary Risk Factors			
Low in Fruits	lip and oral cavity cancer, nasopharynx cancer, other pharynx cancer, esophageal cancer, larynx cancer, tracheal, bronchus, and lung cancer, ischemic heart disease, ischemic stroke, hemorrhagic stroke, diabetes	100 g/day decrease	250 (200-300) grams
Low in Vegetables	ischemic heart disease, ischemic stroke, hemorrhagic stroke	100 g/day decrease	360 (290-430) grams
Low in Legumes	ischemic heart disease	50 g/day decrease	60 (50-70) grams
Low in Whole Grains	ischemic heart disease, ischemic stroke, hemorrhagic stroke, diabetes	50 g/day decrease	125 (100-150) grams
Low in Nuts and Seeds	ischemic heart disease, diabetes	4.05 g/day decrease	20.5 (16-25) grams
Low in Milk	colorectal cancer	226.8 g/day decrease	435 (350-520) grams
High in Red Meat	colorectal cancer, diabetes	100 g/day increase	22.5 (18-27) grams
High in Processed Meat	colorectal cancer, diabetes, ischemic heart disease	50 g/day increase	2 (0-4) grams
Nutrient Based Dietary Risk Factors			
Low in Fiber	colorectal cancer, ischemic heart disease	20 g/day decrease	23.5 (19-28) grams
Low in Calcium	colorectal cancer	1000 mg/day decrease	1150 (1000-1300) grams
Low in Omega3	ischemic heart disease	100 mg/day decrease	250 (200-300) mg
Low in Polyunsaturated Fatty Acids (PUFA)	ischemic heart disease	5% of PFA energy/day decrease	11% (9-13%) of energy
High in Trans-Fatty Acids (TFA)	ischemic heart disease	2% decrease in TFA energy intake	0.5% (0-1%) of energy

Calculation Example

The example of daily micro-disability adjusted life years (µDALYs)/day due to the risk of esophageal cancer for a 25 year old individual consuming 150 grams of fruit will be calculated here. The first step involves the calculation of the relative risk (RR) at various levels of fruit intake based on Global Burden of Disease (GBD) of disease data using linear regression. Given a recommended fruit intake of 250 grams per day (at which there will be zero additional risk (RR=1.0) of esophageal cancer due to adequate fruit intake), and a decrease in consumption of 100 grams per day (at which the RR for esophageal cancer increases to 1.153 for a 25 year old individual), the slope (-0.00153) and b-intercept (1.3825) of the regression line linking the change of grams of fruit intake (TMREL of 250 grams of fruit minus 100 grams of fruit) and change in relative risk ratio relationship (for 25 year olds) (RR of 1.0 at TMREL intake compared to RR of 1.153 at 150 grams of fruit) is calculated using linear regression. In order to translate the risk-exposure relationship to µDALYs per person per day, the attributional fraction (AF) of each age based RR is calculated using Eq. 1. In this example, a person consuming 150 grams of fruit per day would have an attributable fraction of 0.132. This means that of all the people consuming 150 grams of fruit per day (100 grams less than recommended) that get esophageal cancer, 13.2% of these cancers are due to the lower than recommended fruit consumption. Using this number, we can calculate how many esophageal cancer DALYs an individual consuming fruit at this level is responsible for with Eq. 2. Given total DALYs due to esophageal cancer for Western Europe in 2016 (5.8E+05) and a 2016 Western Europe population of 4.28E+08, this means a 25 year old individual consuming 150 grams of fruit per day would be responsible for 4.93E-07 DALYs daily only due to fruit under-consumption. The results of all slopes, intercepts, attributional fractions, and relative risks (associated with the change in consumption on the x-axis and the change in daily µDALYs per person on the y-axis) can be found in Dataset S2. The relationship between dietary risk factor consumption amounts and the relative risk is shown in Figure S1.

This individual's environmental health impact associated with their fruit production was calculated using the Recipe[2] environmental impact assessment method. In this simplified example we will assume the individual consumed 150 grams of apples, however in reality and for the impact calculations in the main paper the fruit consumption of each individual consisted of up to 12 different types of fruits (Dataset S1), each of which has varying degrees of impacts to produce. To produce 150 grams of apple, 7.49E-7 DALYs are produced due to human health effects of global warming, based on the production of greenhouse gases associated with the apple's production. 3.89E-10 DALYs are produced due to stratospheric ozone depletion, 6.1E-11 DALYs are produced due to compounds associated with ionizing radiation from nuclear electricity use, 2.93E-10 DALYs are produced due to compounds associated with ozone formation, 9.84E-8 DALYs are due to particulate matter and aerosol formation, 9.74E-7 DALYs are due to human exposure through water, soil, and air of 99 different carcinogenic substances leading to disease, 3.31E-6 DALYs are due to human exposure of 271 non-carcinogenic substances through water, air, and soil, and 5.96E-8 DALYs are due to the effects of regionally specific water consumption impacts, for a total environmental health impact of 5.19E-6 DALYs to produce 150 grams of apple. The relationship between dietary risk factor consumption amounts and environmental human health impacts is shown in Figure S2. Figure S3 shows the comparison between the sum of environmental human health impacts to produce the foods and the personal health impacts of consuming these foods, with the minimum production impacts necessary to meet recommended intakes of each food group.

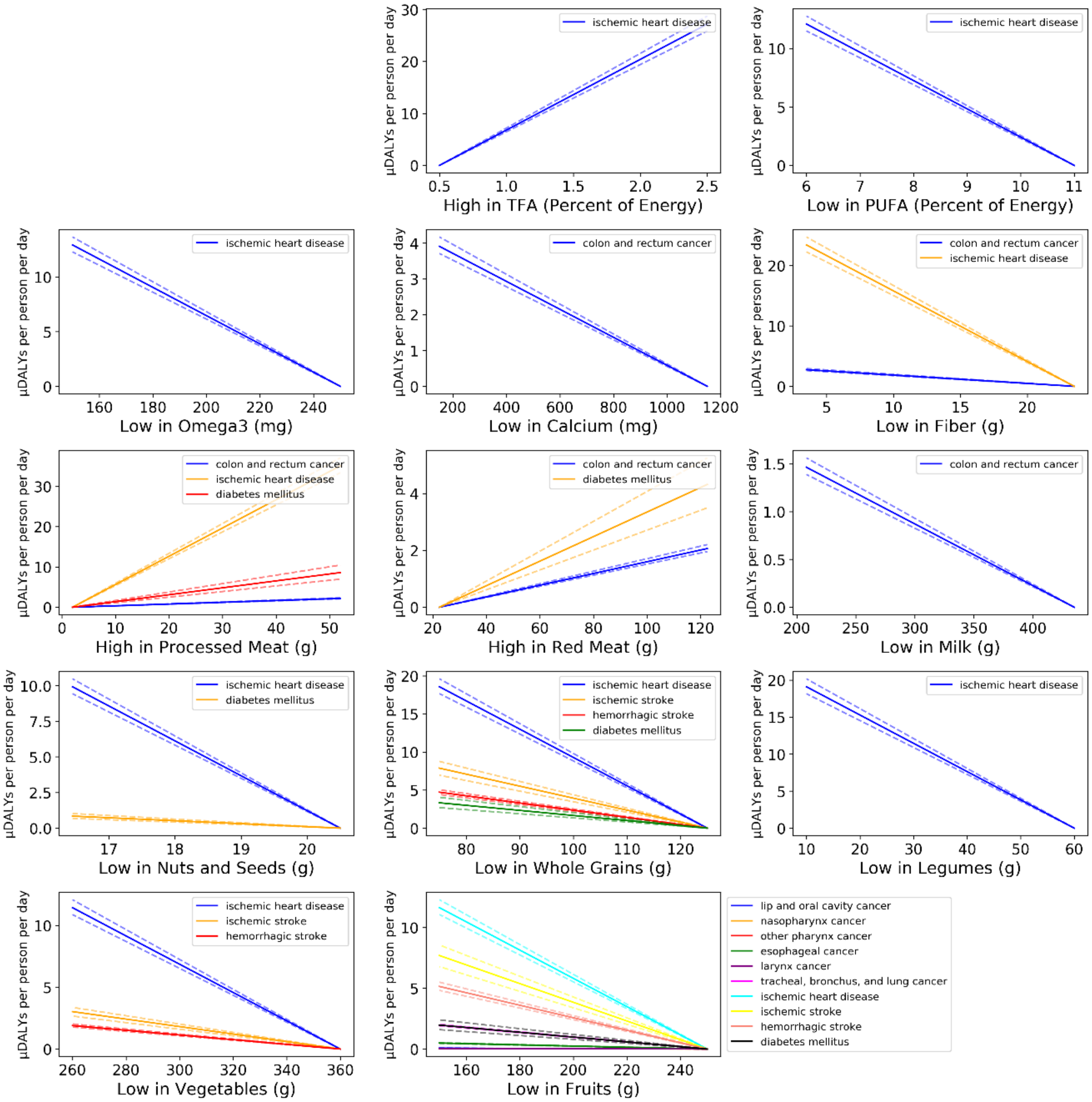

Figure S1. Daily personal health impacts as µDALYs per person due to dietary risk factor-exposure relationships from epidemiological studies as an example. Worst case scenario (relative risks associated with people ages 25-29) relationships are shown. X-axis indicates the change in exposure (either as grams or milligrams of food or nutrient consumed or as percentage of energy intake for polyunsaturated fatty acids (PUFA) or trans-fatty acids (TFA). Y-axis represents the consumption µDALYS per person per day at the given exposure rates. Dashed lines indicate the upper and lower µDALYs for each disease based on uncertainty provided by the GBD visualization tool. Relative risks and changes in exposure are from the GBD[1], DALYs associated with each disease from 2016 are from the GBD visualization tool[3], and population statistics are from the GBD 2016 Population Estimates[4].

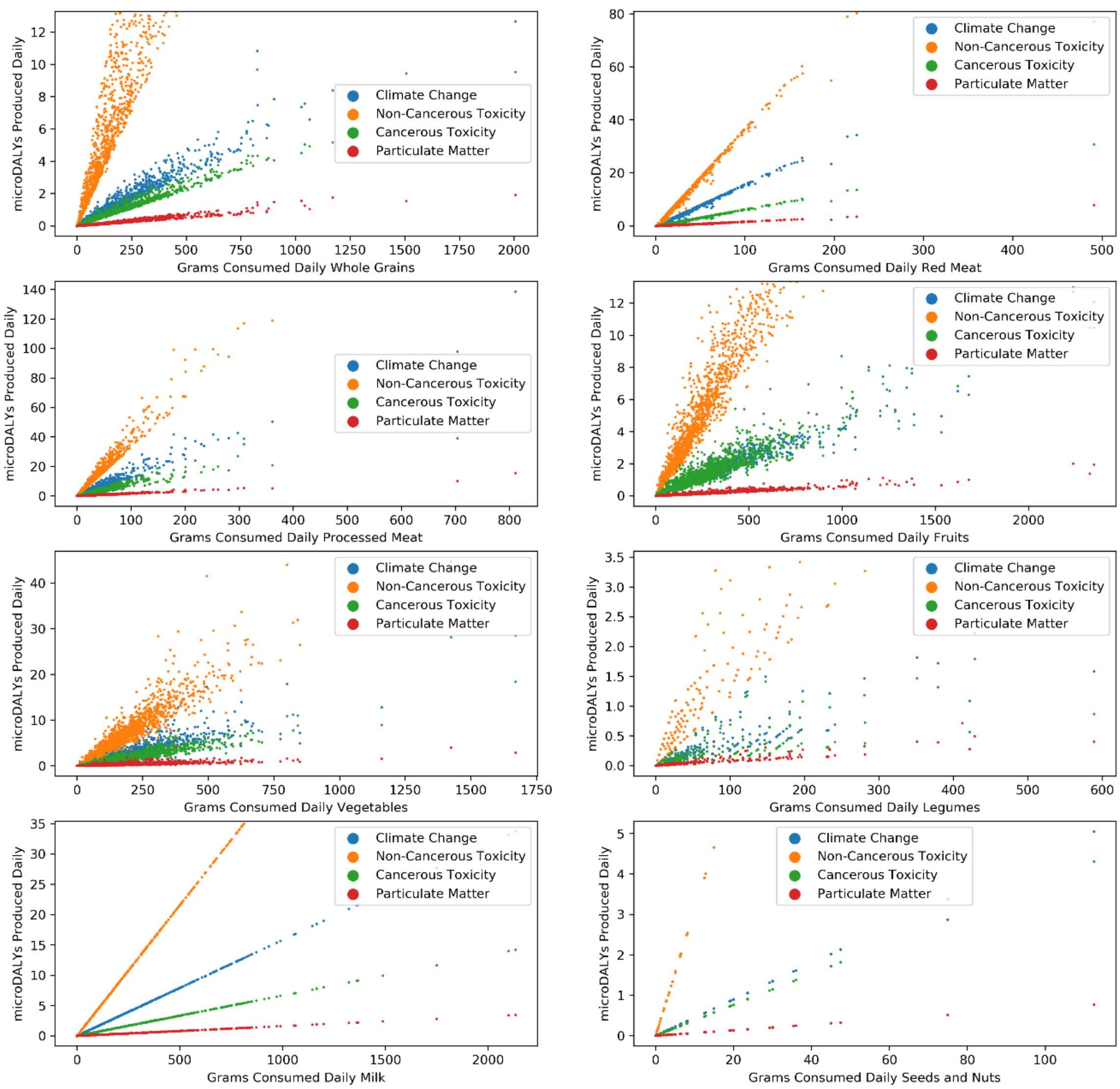

Figure S2. Daily environmental human health impacts as µDALYs per person of producing each type of food group associated with the food-based dietary risk categories, as it was consumed by the sample population's food consumption patterns. Environmental human health impacts are broken down into the four largest categories contributing to a food's impacts. A large spread in impacts occurs when there are many different types of foods (and therefore impacts) considered in one food category (e.g. vegetables), compared to food categories with little/no spread (e.g. milk), in which impact ranges between food items are minimal.

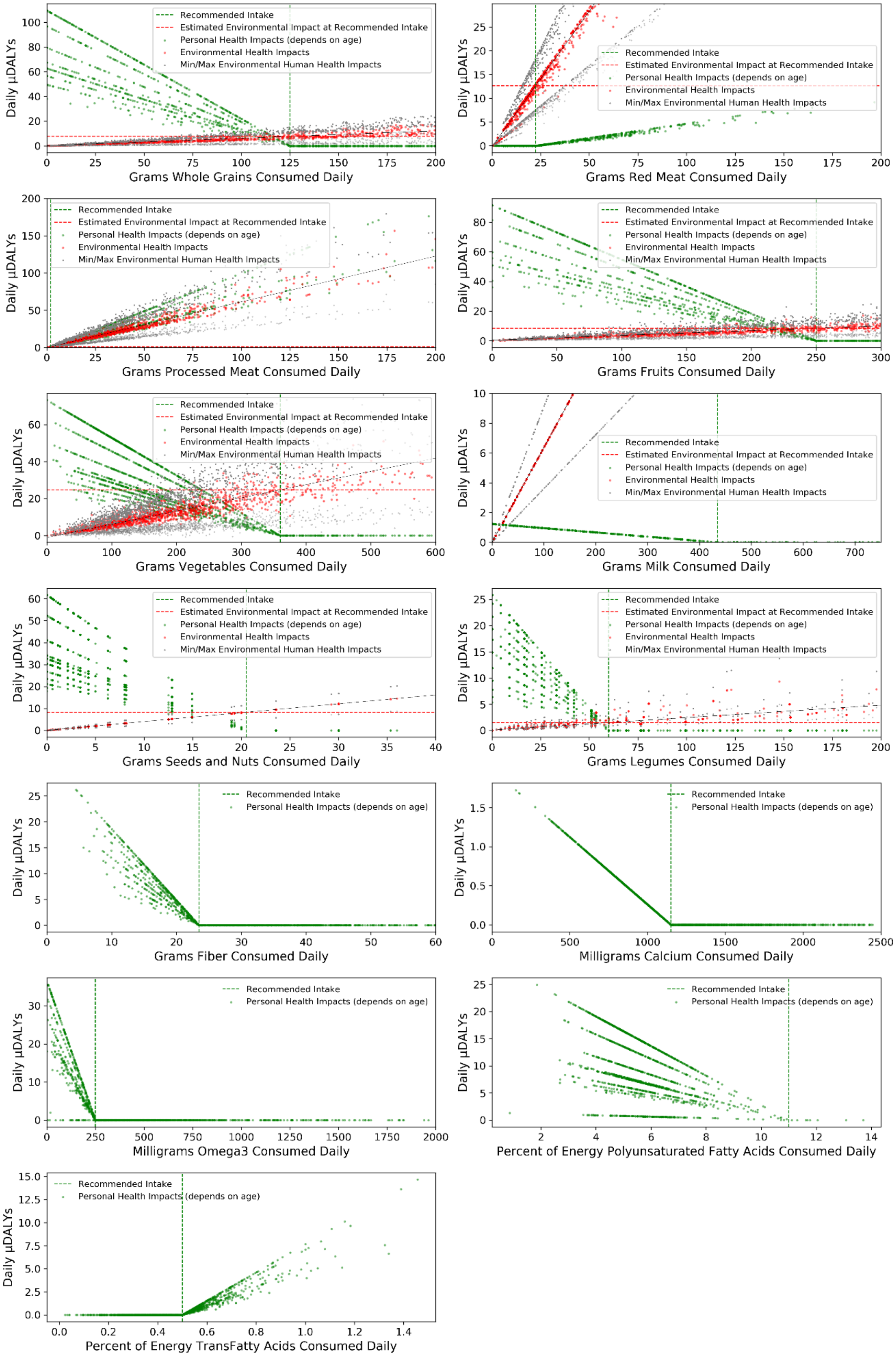
Daily µDALYs
Grams Whole Grains Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Red Meat Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Processed Meat Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Fruits Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Vegetables Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Milk Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Seeds and Nuts Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Legumes Consumed Daily
Recommended Intake
Estimated Environmental Impact at Recommended Intake
Personal Health Impacts (depends on age)
Environmental Health Impacts
Min/Max Environmental Human Health Impacts
Daily µDALYs
Grams Fiber Consumed Daily
Recommended Intake
Personal Health Impacts (depends on age)
Daily µDALYs
Milligrams Calcium Consumed Daily
Recommended Intake
Personal Health Impacts (depends on age)
Daily µDALYs
Milligrams Omega3 Consumed Daily
Recommended Intake
Personal Health Impacts (depends on age)
Daily µDALYs
Percent of Energy Polyunsaturated Fatty Acids Consumed Daily
Recommended Intake
Personal Health Impacts (depends on age)
Daily µDALYs
Percent of Energy TransFatty Acids Consumed Daily
Recommended Intake
Personal Health Impacts (depends on age)

Figure S3. Plots of daily μDALYs associated with an individual's personal health impacts (green dots) and environmental human health impacts (red dots) compared to dietary risk exposure values for each dietary risk category. Recommended consumption values (TMREL) are shown as vertical green dashed lines and the estimated environmental human health impacts associated with recommended consumption, based on linear regression, are shown as horizontal red dashed lines. No environmental human health impacts are shown for nutrient based dietary risk factors, as these were analyzed separately. Environmental human health impacts (red) are not dependent on age, however, personal health impacts (green) do change depending on age (as RR values for many diseases are dependent on an individual's age), which is why there are several different personal health impact lines. Environmental human health impacts uncertainties as they were calculated by the SimaPro software are shown as gray dots.

Additional Results

Production impacts of nutrients

There are five nutrient based GBD dietary risk factors (calcium, omega 3, dietary fiber, polyunsaturated fatty acids (PUFA), and trans fatty acids (TFA)) for which environmental human health impacts were not considered. An additional analysis was conducted to determine what food group would have the lowest environmental human health impacts to provide each specific nutrient. The top three food group providers (of 12 considered – shown in Dataset S1) for each nutrient were considered, with the results shown in Table S2. Numbers in the table show the average percentage of the total nutrient consumed that was provided by each food group for this sample population. Others represents the contribution total of the other nine remaining food groups not shown.

Table S2. The five nutrient based GBD dietary risks are shown with the largest food group sources of each nutrient. The numbers represent the percentage of the specific nutrient provided by that food group for the daily requirement to prevent disease, based on the sample population's eating patterns.

	Nutrient				
	Calcium	**Omega 3**	**Dietary Fiber**	**PUFA**	**TFA**
Food Groups	Dairy: 40%	Meat/Fish: 86%	Bread: 22%	Meat/Fish: 19%	Dairy: 33%
	Bread: 16%	Eggs: 9%	Vegetables: 22%	Sweets: 17%	Meat/Fish: 31%
	Sweets: 8%	Sweets: 2%	Fruit: 22%	Fats: 14%	Sweets: 19%
	Others: 36%	Others: 3%	Others: 34%	Others: 50%	Others: 17%

Figure S4 shows the relationship between personal health impacts due to over or under-consumption of a specific nutrient (x-axis) and the environmental human health impacts that would be necessary to produce foods that would provide that nutrient. The largest supplier of calcium in this sample population was dairy products, followed by bread and then sweets (Table S2). For individuals under-consuming calcium, the food group with the largest environmental health impacts as μDALYs to provide this missing calcium are connected with the sweets and snacks (Figure S4a), the next largest impacts are associated with dairy products, and the lowest impacts are associated with the breads and savory biscuits. This means that individuals requiring additional calcium should source it from bread products for the lowest environmental human health impacts associated with production. Results were less clear for the other nutrients, however, eggs were shown to have the lowest environmental human health impacts for omega 3, bread or fruits to have the lowest impact as a dietary fiber source, and fats and spreads were the least damaging to environmental human health as a poly unsaturated fatty acid source. Trans fatty acids are included in Figure S4e, however since consumption of this nutrient should be minimized, the lowest impact food source is irrelevant.

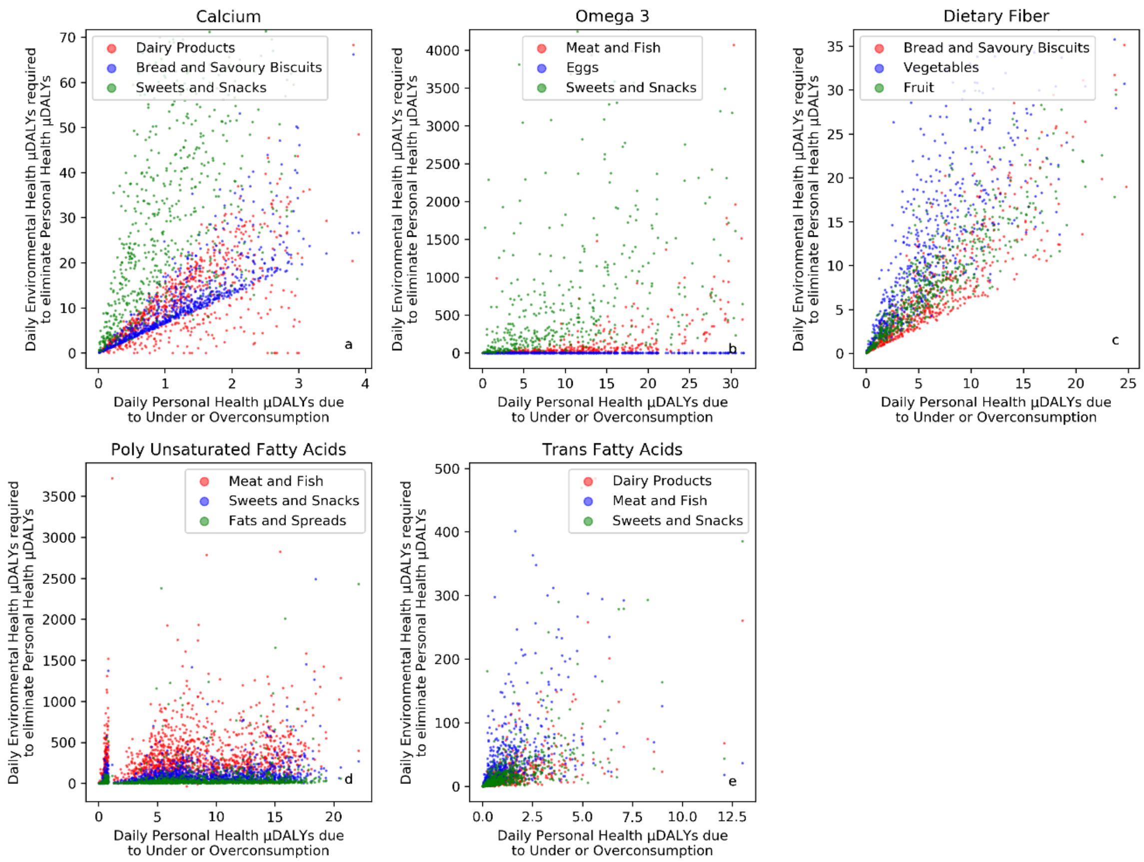

Figure S4. Comparison of daily environmental human health impacts (y-axis) necessary per individual to eliminate personal health impacts as µDALYs (x-axis) across various food groups for each nutrient based GBD dietary risk factor as they compare to personal health impacts for either under-consumption (a through d) or overconsumption (e).

Sensitivity Analysis to changing GBD factors

In this analysis, the GBD DALYs attributable to each disease were taken from the Western European 2016 DALY estimations (and the associated 2016 Western European populations). A sensitivity analysis was completed to see how the results would change using the corresponding Global DALY disease specific estimations and populations. Changes in Impact Ratio values shown in Figure 2 of the manuscript are summarized in Table S3 below. In addition, a sensitivity analysis was also completed to estimate changes in the Impact Ratios that would occur by shifting the TMREL value, given that studies outside of the GBD have found health benefits of consuming higher (or lower) intakes than what the GBD recommends.

Table S3. Results of the sensitivity analysis for comparing Global DALYs to Western European DALYs and results of the sensitivity analysis for changing TMREL (daily recommended intake values). Numbers indicate the Impact Ratio (shown in Figure 2) values that would result in these changes, compared to the Impact Ratio values shown in the main text (Reference).

Dietary Risk Factor	Reference Western European DALYs Average TMREL	Sensitivity Analysis 1 Global DALYs Average TMREL	Sensitivity Analysis 2 Western European DALYs Min TMREL	Sensitivity Analysis 3 Western European DALYs Max TMREL
Whole Grains	-7.7	-9.8	-7.9	-7.8
Fruit	-5.7	-7.1	-5.4	-5.9
Vegetables	-1.5	-1.9	-1.5	-1.5
Nuts and Seeds	-5.0	-5.7	-5.0	-5.0
Legumes	-7.3	-8.2	-7.7	-7.5
Milk	-0.1	-0.0	-0.1	-0.1
Processed Meat	1.1	1.24	1.1	1.1
Red Meat	0.1	0.1	0.1	0.1

Comparison with other environmental impact categories and previous investigations

On average, for this population sample, an individual's total daily diet was responsible for 6.1 ± 2.8 kgCO2 equivalents for climate change, 267 ± 108 liter equivalents for water scarcity, 4.84E-14 ± 2.8E-14 potentially disappeared fractions*year for biodiversity loss[5], and 200.0 ± 83.5 µDALYs as environmental human health impacts per person per day, not including any additional µDALYs due to personal health impacts.

The relationship between total personal health impact as µDALYs with each of the total diet environmental impact categories is shown in Figure S5a-d. As with the comparison of total personal health impact DALYs to the total diet environmental human health impacts as DALYs (Figure 4), there was no correlation for each of the other environmental impact indicators (climate change: r^2=0.012, water scarcity footprint: r^2=0.014, and biodiversity loss: r^2=0.05).

In order to compare the diet quality aspect of the results found here to previous work that has been done on this same sample population[5], the relationship between the ratio of the average nutrient intake (both beneficial and harmful) and daily total personal health impact was investigated. Beneficial nutrient intake considered the average intake ratio (amount consumed divided by amount recommended) of nineteen macro and micronutrients. A value of 1.0 indicated that the individual consumed the average recommended intake amounts based on their age and gender, and any value less than 1.0 indicated that one or more nutrients were under-consumed. Harmful nutrient intake considered the average intake ratio of saturated fats, sugars, and sodium, with a value of 1.0 indicating that an individual did not consume more than was recommended, and any value above 1.0 indicating that one or more of these nutrients were over-consumed. Details of calculation methods for the average nutrient intakes can be found in Walker et al.[5], and the result of how these values compare to the total personal health impacts as µDALYs are shown in Figure S5e-f.

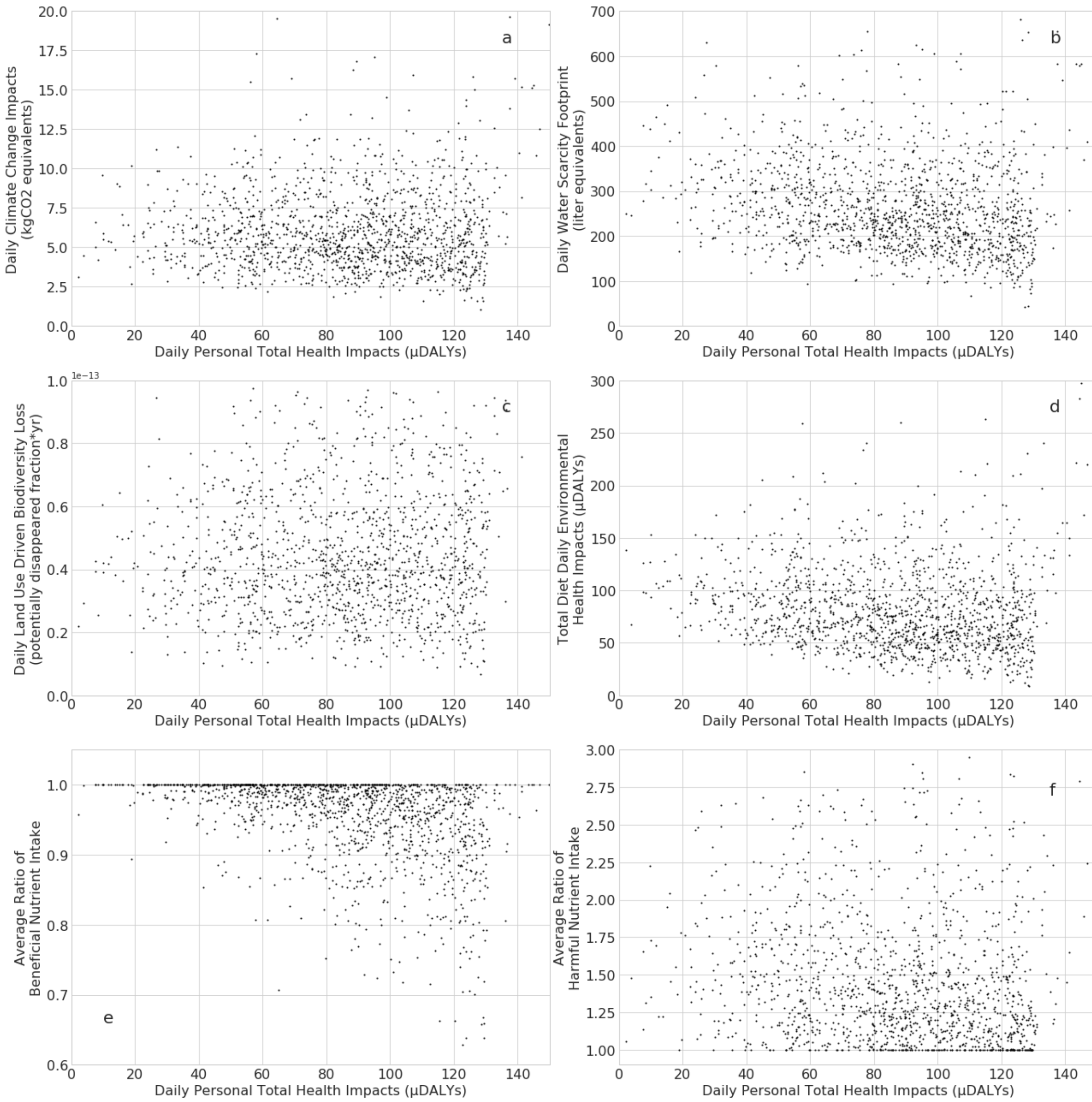

Figure S5. The relationship between each individual's total personal health impacts as μDALYs (x-axis) and their total diet environmental impacts measured as a) climate change (kgCO_2 equivalents), b) water scarcity footprint (liter equivalents), c) land use driven biodiversity loss (potentially disappeared fraction*years), d) environmental human health impacts as μDALYs, e) the average ratio of beneficial nutrient intake and f) the average ratio of harmful nutrient intake. Details of the average ratio of beneficial nutrient intake and harmful nutrient intake are included above and in Walker et al.[5]

Additional data table S1 (separate file)

Environmental Impacts measured as human health from ReCiPe 2016.
Additional data table S1 (separate file)

Additional data table S2 (separate file)

Relative Risks and Attributional Fractions for age specific disease-dietary risk combinations.
Additional data table S2 (separate file)

References

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Supplementary Information

Comparing environmental and personal health impacts of individual food c

Christie Walker [a,1]

[a] Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

[1] Corresponding author E-mail: walker@ifu.baug.ethz.ch; phone: +41-44-633-7145

This file contains:

Dataset S1 - Environmental Impacts measured as human health from ReCiPe 2016 Egalitarian choices

Supplementary Information

Comparing environmental and personal health impacts of individual food c

Christie Walker [a,1]

[a] Institute of Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

[1] Corresponding author E-mail: walker@ifu.baug.ethz.ch; phone: +41-44-633-7145

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Dataset S2 - Relative Risks and Attributional Fractions for age specific disease-dietary risk combinations

choices